Modeling a Radiant Slab Coupled to a Cooling Tower using the New National Energy Analysis Program

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INTRODUCTION

What if? When one considers all of the questions that one might ask during the design of any building, product, technology, etc., the most intriguing questions might be the ones that begin with "what if". Questions posed in such a way tend to be less from a practical standpoint and more from a visionary standpoint. In many cases, even when the thought posed in the "what if" question cannot be satisfied, the end result of asking such a question may be a better solution than if one had simply contemplated would could be done.

In the design of a building, many "what if" questions might be posed by either the architect or the engineers associated with the project. Unfortunately, because a building tends to be a major investment, there is a natural tendency to be cautious and perhaps not push the limits of what is possible. Yet, if design solutions can be investigated without first going through the expensive building process, the number of "what if" questions might increase and the result might be improvements in design as well as energy efficiency of buildings.

This is where thermal simulations can play a vital role in the design process. When appropriate models exist, architects and engineers can explore a wide variety of options that might improve the efficiency of buildings in the design phase before they are built. Simulation is an inexpensive means for exploring a plethora of different design options and HVAC systems.

Unfortunately, models do not always exists and even when they do exist they may not accurately account for the complex interactions that are encountered within a building. This has been a particular hindrance to radiant systems. Forced air conventional systems have dominated the American HVAC landscape for quite some time. Air-based systems are relatively easy to control, understand, and model, and this may partially explain their popularity with the general public. Radiant systems are less easily controlled and understood, and the models of radiant systems have not been able to achieve the same accuracy and flexibility as models for conventional systems.

With the release of the new national energy analysis program (EnergyPlus), this has changed. For the first time, a major, publicly available simulation program has an integrated radiant system model. Now, architects and engineers can ask the question "what if we install a radiant system in this building" and be able to come up with an answer as to whether that might improve the energy efficiency of the building. This paper endeavors to demonstrate that the new program is also a good tool for asking further "what if" questions such as "what if a floor slab radiant system is coupled to a cooling tower to use 'free-cooling' and the thermal mass of the floor slab is used to help the space coast through the day?" Moreover, "what if the building is in a less than ideal climate (one with relatively high humidity levels)?"

PROGRAM OVERVIEW

The model used within the EnergyPlus program is based upon the heat balance solution technique described in the ASHRAE Loads Toolkit (Pedersen 2001) and that was used in the BLAST program (Building Systems Laboratory 1997). The basic methodology is to apply the First Law of Thermodynamics at both the inside and outside surface of all building elements as well as on control volumes surrounding the air within the various thermal zones of the building. In each control volume, all of the thermal forces due to conduction, convection, and long and short wavelength radiation that are appropriate for the type of control volume are balanced. This results in equations that can be solved for surface temperatures and either the temperature of the zone air or the amount of heating or cooling that must be provided by the HVAC system to maintain a particular setpoint temperature.

While the scope of this paper does not allow for the complete discussion of the heat balance method as it is applied within the EnergyPlus program, several of the key assumptions and characteristics are described below.

- Transient conduction is solved using conduction transfer functions that are derived using the state space method
- Uniform surface temperatures (at any given point in time, each building element is characterized by a single temperature at the interior side and a single temperature at the exterior side; larger surfaces may be broken up into multiple surfaces for better temperature differentiation)
- Diffusely radiating surfaces
- Interior and exterior convection correlation that depend on flow conditions and temperature differences
- Well-stirred zone air (air temperature is constant throughout the zone/no stratification)
- Zone time steps are allowed to be less than an hour

One of the key features of EnergyPlus that is important to the modeling of radiant systems is the fact that the zone, system, and plant simulations are integrated (Taylor 1991). Rather than simulating all of the loads based on an assumed system capacity, EnergyPlus simulates the thermal envelope and the primary and secondary systems simultaneously. This allows feedback from the plant and the system back to the zone conditions. This is particular critical when modeling a radiant system that serves as both a building envelope element and a space conditioning system.

One of the main goals of EnergyPlus was to ensure the flexibility and modularity of the new program. Legacy codes (DOE-2 and BLAST) that formed the basis for EnergyPlus had many of the common drawbacks of monolithic simulations programs. One problem was the lack of flexibility within the models. This meant that it was sometimes difficult to model common situations with the standard systems that were included in the programs. Moreover, small differences from the standard systems meant that either the current model would have to be updated or a new model developed. This generally required a significant amount of expertise in the programs and then a substantial amount of resources. Often, model development lagged well behind industry developments. The flexibility of existing models within EnergyPlus and its modularity allow more common situations to be simulated and much faster development time for new models. It is hoped that this will benefit the simulation community in many ways and the users by providing more simulation capabilities within a shorter time frame.

The EnergyPlus radiant system model is one example of how the flexibility and modularity of the new program have already paid dividends. The radiant system model is integrated within the HVAC structure of the program but is able to link back to the heat balance since the radiant system can also affect surfaces within the thermal zones. Surfaces are allowed to have embedded heat sources (or sinks) that can either be electrical or hydronic. This addition or subtraction of heat within a building element required the modification of the standard conduction transfer functions (Strand and Pedersen 1994, Strand 1995). The resulting equations were integrating with the standard heat balance formulation and did not require the rewriting of the heat balance equations. In fact, the new conduction transfer function series are calculated alongside the standard series terms and the heat balance equations simply have an addition term to take the heat source/sink into account. The HVAC side of the radiant system model is simply a heat exchanger that is connected to a water loop (Strand and Pedersen 1997). Water is conditioned by boilers, chillers, etc. and circulated through the slab or panel using a pump.

Controls for the radiant system model are flow-based controls that can simulate a variety of thermostat types. The user can decide whether the quantity within a space that is to be controlled is the mean air temperature, the mean radiant temperature, or the “operative” temperature (defined simply as the average of the mean air and radiant temperatures for control purposes). The deviation of conditions within the space from the setpoint will trigger the system to send more or less conditioned water (or electrical current) through the radiant slab or panel. This is defined as a simple linear function where the user has control over both the throttling range and the "gain" (Strand and Pedersen 2002). The user also has the ability to look at the resulting thermal comfort within the space using one of three established thermal comfort models (Lee 2001).

FREE-COOLING APPROXIMATION AND CASE STUDY

The goal of this study was to show that even though the radiant system model within the new program is only a first step and still relatively simple, the program itself is flexible enough to allow the analysis of more complex situations. The system configuration for this paper is the coupling of a fairly massive radiant slab with a water loop that is run through a cooling tower. The purpose for this is to see how this affects the cooling loads for a typical residential construction in a fairly humid climate. During the day, there would be a standard convective system (DX) that would meet any of the space conditioning loads that were not met by the radiant slab. In reality, this type of configuration is a complex "hybrid" system with sophisticated controls and has the possibility to run the radiant and convective at the same time. In most cases, the radiant slab is not connected to a cooling tower but rather to a chiller loop.

Currently, it is not possible to model a radiant slab that is directly connected to a cooling tower in EnergyPlus, but it is possible to mimic the situation through utilization of some of the existing features of the program. The approach to modeling a radiant slab that is connected to a cooling tower within the current capabilities of EnergyPlus was to obtain the hourly wet-bulb temperatures and use those conditions to schedule the water loop setpoint temperature. In EnergyPlus, it is possible to vary a loop temperature on an hourly basis. Since it is not yet possible to connect a cooling tower directly to a radiant system within the program, this connection was simulated by scheduling the water loop setpoint temperature to approximately 5°F above the outdoor wet-bulb temperature. This approximates the performance of a cooling tower well enough for this study. The water was conditioned to the appropriate setpoint by "purchased cooling".

While two systems can operate at the same time on the same thermal zone within EnergyPlus, it was decided that the main goal for this study was to "pre-cool" the floor slab within the residential building and then achieve comfortable conditions by running the DX system during the day. System operation can also be scheduled and prioritized in the program so the radiant slab was scheduled to run between 8pm and 7am while the DX system was scheduled to run the remaining portion of the day. The goal was to cool off the slab as much as possible when the wet-bulb temperatures were low enough to reduce, if possible, the loads that would be met by the DX system. The best hours of operation for the radiant system were determined by numerical experiment.

The building this combined system was tested in was a fairly typical residential building. The home is assumed to have approximately 1500ft^2 of living space (50 ft along the east-west axis, 30 ft along the north-south axis), an attached garage (400 ft^2) on the north side of the building, an attic above the living space and garage, and a fairly lightweight construction (metal siding). A reasonable amount of double pane windows were placed on all of the exterior walls and an overhang was defined over the entire length of the south wall to cut down on solar gains during the summer. The floor was a slab-on-grade floor with 2" of insulation under the entire slab. For modeling purposes, 12" of dirt was added below the insulation to separate the building somewhat from the deep ground temperature. The building was located in Rantoul, IL (former home of Chanute AFB) and simulated using summer design day weather conditions for that location. Internal gains were set at 0.5 W/ft^2 for lights and equipment (combined) and two adults. Infiltration was kept at 0.5ACH constantly during the entire 24 hours of the day. The living space was controlled to 77°F while the attic and garage areas where left unconditioned.

The radiant system consisted of 0.5" diameter tubing embedded in the center of an 8" thick layer of concrete (2" and 4" were also investigated). The water flow rate through the tubing was approximately 20GPM. The system was controlled to achieve the same mean air temperature as a conventional system. This handicaps the radiant system slightly since the cooler temperature of the slab should result in a lower mean radiant temperature for the combined system when compared to a conventional forced-air system. The DX system that was run during the daytime hours was nominally a 3-ton unit.

RESULTS

Two sets of runs were performed using the system and data described in the previous section. First, a comparison was made between the residential building without either the radiant system or the DX system and with the radiant system only (running from 8pm through 7am). In neither of these runs were the conditions within the house acceptable during the day. While the radiant system did moderate the temperature increase during the warmest portion of the day, the decrease of peak temperature from approximately 87°F to 83°F was not enough to maintain comfortable conditions within the house.

The second set of comparisons was made between an air only system and the DX system assisted by the nighttime operation of the radiant system served by the cooling tower. In both cases, the goal was to maintain an air temperature within the living space of 78°F. In addition, the amount of concrete in the floor slab was also varied between successive runs to determine the effect of the amount of mass and also to note if there was an optimal amount of concrete for this particular case. In all cases, the hydronic tubes were assumed to be in the middle of the concrete layer. The results are shown in (Table 1) below.

TABLE 1. SIMULATION RESULTS FOR CONDITIONED RESIDENTIAL BUILDING

Case	*Total Cooling Required by the Air System*
Air System Only	94.5 kBtu
DX/Radiant System (2" concrete)	65.6 kBtu
DX/Radiant System (4" concrete)	45.2 kBtu
DX/Radiant System (8" concrete)	38.2 kBtu

Despite the fact that the outdoor wet-bulb varies from a low of 66°F to a peak of 73°F during the day, it appears that the slab can be cooled enough (provided a large enough cooling tower exists) to significantly reduce the cooling that must be provided by the DX system even with the assumption of a fairly humid climate and that the temperature of the water leaving the cooling tower is about 5°F higher than the wet-bulb temperature. While these results are encouraging, further study and comparison with field data would be necessary before such reductions in cooling loads can be taken at face value.

CONCLUDING REMARKS

The question of "what if" asks not what can be done but what could be done. This paper intended to show what can currently be done with the new national energy analysis program and points the way toward what could be done in the future by enhancing the existing radiant system model. Areas for future work include increased coordination between the simultaneous operation of radiant and convective systems ("hybrid" systems), more sophisticated and flexible controls (including hydronic temperature controls), and a seamless link between the radiant slab and other fluid loops besides the chilled water loop (such as a condenser loop that is connected to a cooling tower, ground loop, etc.).

All of these improvements will lead to an expansion of what the program can simulate and will lead to further ideas on improvements to the model as designers continue to ask "what if" questions. The example shown in this paper is evidence that such improvements might lead to more energy efficient designs even in locations that are not thought to be particularly conducive to such creative solutions. This is one of the main benefits of thermal simulations: providing reliable answers to questions about what could be done before the building is even built.

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